

The Star-formation History of the Universe as Revealed from Deep Radio Observations of the 13^H XMM-Newton/Chandra Deep Field

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Abstract. Discerning the exact nature of the faint (sub-mJy) radio population has been historically difficult due to the low luminosity of these sources at most wavelengths. Using deep observations from *Chandra/XMM-Newton/Spitzer* and ground based follow up we are able to disentangle the AGN and star-forming populations for the first time in a deep multi-frequency GMRT/VLA/MERLIN Survey. The many diagnostics include radio luminosity, morphology, radio to mid-IR flux density ratios, radio to optical flux density ratios and radio spectral indices. Further diagnostics, e.g. optical spectra, X-ray spectra/hardness ratios, IR colours indicate the presence of the AGN *independent* of whether the radio emission is powered by AGN or star-formation. We are able to examine the star-formation history of the universe up to $z = 2.5$ in a unique way based on an unbiased star-formation rate indicator, radio luminosity. This work provides an alternative perspective on the distribution of star-formation by mass, “downsizing” and allows us to examine the prevalence of AGN in star-bursts.

1. Introduction

Above a flux density of 1 mJy the sources which dominate the 1.4 GHz radio source counts are almost exclusively AGN. However below 1 mJy there is an excess over the extrapolation from higher fluxes which is known as the “sub-mJy bump” (Richards 2000; Hopkins et al. 2003; Seymour et al. 2004). The conventional view is that the bump arises from star-burst emission (Condon 1992; Richards 2000). Attempts to determine the separate evolution of the star-burst and AGN populations have been severely hampered by the scarcity of genuine multi-wavelength data sets on deep radio surveys. Source evolution is constrained, rather poorly, only by the shape of the source counts (e.g. Hopkins et al. 2003; Seymour et al. 2004, Moss et al. in prep.)

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Only now with the advent of multi-wavelength data sets from X-ray to radio are we able to distinguish with confidence the nature of the radio emission for virtually all the sub-mJy radio population. This work is based on a deep radio surveys of the 13^H *XMM-Newton/Chandra* Deep Survey Field. In addition to ~ 16 days of MERLIN data, we have very deep observations at two frequencies: 1.4 GHz down to $\text{rms} \sim 7 \mu\text{Jy}$ from the VLA (Seymour et al. 2004) and 610 MHz down $\sim 25 \mu\text{Jy}$ from the GMRT (Moss et al. in prep.). If we are able to distinguish between AGN and star-forming galaxies (SFGs) we will have an unbiased view of the star-formation history of the universe as radio luminosity is a direct tracer of the star-formation rate.

2. The Multi-wavelength Data Set

We have a legion of complimentary data. Our deep multi-wavelength optical imaging from $0.3 - 2.2 \mu\text{m}$ allows us to derive photometric redshifts for the $\sim 60\%$ of sources without spectroscopic redshifts (Dwelly et al. in prep).

We also have deep X-ray data (McHardy et al. 2003; Loaring et al. 2005; Page et al. 2006) from *XMM-Newton* and *Chandra* as well deep observations from GTO *Spitzer* with the IRAC and MIPS instruments.

3. Radio Emission and AGN Diagnostics

The following diagnostics help us determine if the radio emission is due to AGN or star-formation activity:

a) Radio luminosity: any sources with radio luminosities greater than 10^{25} WHz^{-1} are taken to be AGN.

b) Radio morphology: objects with extended morphology, e.g. lobes and jets, not associated with the underlying galaxy are taken to be AGN, but if the morphology matches the underlying galaxy they are taken to be SFGs.

c) Radio to mid-IR flux density ratio: any radio source with a $24 \mu\text{m}$ to 1.4 GHz flux density ratio more than 0.3dex below that for the most extreme star-forming galaxies are taken to be AGN.

d) Radio to optical flux density ratio: objects with radio to optical flux density ratios greater than 10 are taken to AGN.

e) Radio spectral index: any sources with radio spectral indices not in the range $-0.5 < \alpha < -1$ are taken to be AGN.

Indicators of the presence of AGN, independent of physical cause of the radio emission, include: optical spectra, mid-IR colours, X-ray luminosities and spectra.

4. Radio Counts by Galaxy Type

Using these radio emission diagnostics we find that $\sim 43\%$ of the sources below $600 \mu\text{Jy}$ are AGN, $\sim 52\%$ are SFGs and $\sim 5\%$ are unknown. These $\sim 5\%$ have no optical/near-IR counterparts and are assumed to be AGN at $z > 2.5$. We are then able to re-derive the normalised Euclidean counts by galaxy type in Fig. 1. The counts by type show the rapid increase in the star-

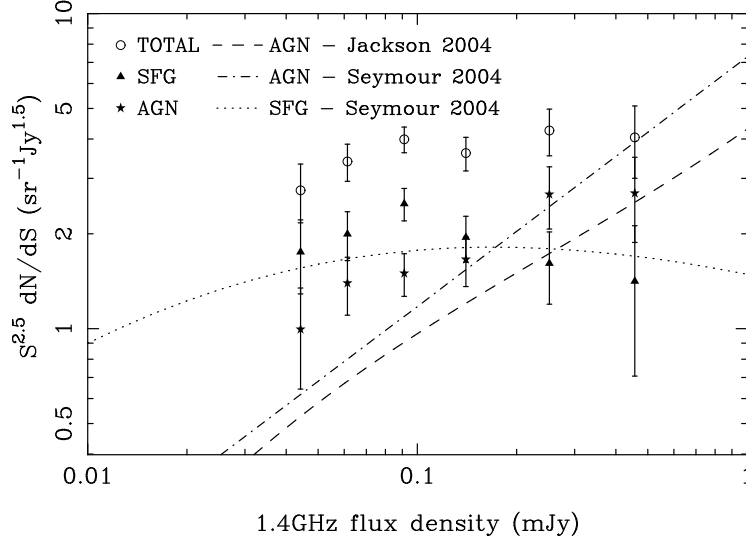


Figure 1. The 1.4 GHz normalised Euclidean source counts. The total counts are indicated by open circles, the contribution from radio AGN by stars and the contribution from radio star-forming galaxies by triangles. We overlay models for different components from Seymour et al. (2004) based on models by Hopkins et al. (1998) and Jackson (2004). Part of the sub-mJy up-turn appears to be due to a rise in the AGN contribution as well as that of the star-forming population.

forming population as predicted by Hopkins et al. (1998); Seymour et al. (2004) and references therein. However the contribution due to AGN does not decrease with flux density as rapidly as predicted by models extrapolated from higher flux densities and appears to contribute about 30% of the faint counts below 0.1 mJy.

5. Star-formation History of the Universe Across $0 \lesssim z \lesssim 2.5$

With the successful separation of AGN and star-forming galaxies in our survey we are able to derive the star-formation rate density as a function of redshift (e.g. Lilly et al. 1996; Madau et al. 1996). The star-formation rate (SFR) is derived from the radio luminosity using the relations of Bell (2003) and then the SFR density as a function of redshift is determined by the $1/V_{max}$ method. The correction for the contribution to the total star-formation rate density in a given bin due to the radio sources below our detection limit is determined from our derivation of the evolution of the radio luminosity function (Dwelly et al. in prep.). We are further able to derive the contribution by stellar mass to the total star-formation rate density at each redshift using stellar masses determined from optical-near/mid-IR SED fitting, showing clear evidence of “downsizing” (see fig. 2) The fraction of AGN in the radio SFGs varies from $\sim 20\%$ at low redshift to $\sim 60\%$ in the highest redshift bin suggesting that AGNs may play a crucial role in star-bursts at the peak redshift of star-formation, $1 \lesssim z \lesssim 2.5$.

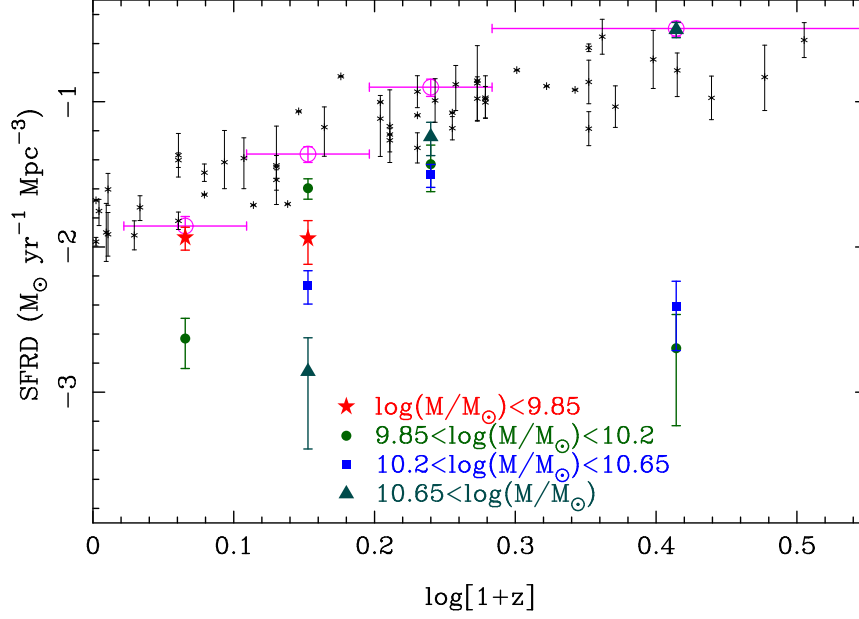


Figure 2. Here we present the star-formation rate density of the universe across $0 \lesssim z \lesssim 2.5$. The small black asterisks are from a compilation by Hopkins et al. 2004. The open circles are the total contribution from the faint radio population where the vertical error bars represent Poisson statistics and the horizontal ones the width of the bin in redshift. The stars, circles, squares and triangles represent the contribution in each bin from galaxies of different stellar mass with horizontal error bars omitted for clarity.

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